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— GODDARD SPACE FLIGHT CENTER —
GREENBELT, MARYLAND

APPLICATIONS OF REMOTE SENSING
TO WATERSHED MANAGEMENT

Albert Rango

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ABSTRACT

Present aircraft and satellite remote sensing systems (operational and experimental) are capable of contributing greatly to watershed management, primarily in the areas of snow mapping, surface water inventories, flood management, hydrologic land use monitoring, and watershed modeling. The two most widely applicable remote sensors are the Multispectral Scanner Subsystem on LANDSAT and the basic multispectral camera array flown on high altitude aircraft such as the U-2. Other aspects of watershed management will be investigated with future aircraft and spacecraft systems possessing higher resolutions and/or covering different spectral wavelength bands such as microwaves. The development of techniques for assessing soil moisture from remote sensing observations would provide a significant breakthrough in hydrology. As the technological advances in remote sensing of hydrological data continue to accelerate, so must the watershed management community expand its awareness of and its training in remote sensing techniques if these new tools are to be put to optimum use.

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APPLICATIONS OF REMOTE SENSING TO WATERSHED MANAGEMENT

By Albert Rango¹

INTRODUCTION

Remote sensing from space started in 1960 with the launch of the first meteorological satellite, TIROS 1. Several generations of meteorological satellites have been flown in the intervening years that have been of some interest to the hydrologic community. Manned space flights began in the mid-1960's, and special photography experiments revealed much useful information to a variety of interested earth scientists. Color and black and white imagery of snowfields and surface water caught the interest of some hydrologists and watershed managers and initial investigative studies were begun. Because of positive results produced by the initial investigators an earth resources satellite called LANDSAT-1 (formerly termed ERTS-1) was launched on 23 July 1972 followed by the launch of LANDSAT-2 on 22 January 1975. The data from these two experimental satellites, the Nimbus research satellite series, and the operational environmental NOAA satellites are currently being used in a wide ranging series of investigations by many scientists concerned with water resources. The results of these latest studies with LANDSAT data are well documented by Freden and Mercanti (11) and Freden, Mercanti, and Becker (12).

CURRENTLY AVAILABLE REMOTE SENSING SYSTEMS

Remote sensing in earth science is not new and existed prior to 1960 through the employment of aerial photography. Low and medium altitude aircraft have been used for snow surveys, soil mapping, highway location, oil and mineral surveys, and land use planning. Although these efforts existed prior to 1960, it appears that the launching of LANDSAT has served to increase interest in the water resources community for exploring in more detail the applications of remote sensing (10). Various types of remote sensing instruments and platforms are available (some especially tailored for water problems) to water resources investigators, but presently the most widely applicable sensors are the Multispectral Scanner Subsystem (MSS) on LANDSAT and the basic multispectral camera array flown on high altitude aircraft such as the U-2. LANDSAT, providing repetitive, regional hydrologic information from 910 km altitude, and the U-2, providing high resolution, small area coverage from about 20 km altitude, tend to complement each other over a wide range of basin size and watershed management activities.

Remote sensing flights from low and medium altitude aircraft can generally be tailored to suit the user and can be contracted for from a variety of private concerns and governmental agencies. High altitude missions are flown frequently by NASA's Earth Resources Aircraft Project (ERAP) in support of various satellite missions and other earth science related research projects. The high altitude remote sensing platforms combine the advantages of satellite sensors and low altitude aircraft by being able to obtain high resolution data over medium size watersheds. The sensor package of ERAP has evolved since 1971 to fulfill a broad spectrum of investigator requirements and needs and, as such, should be applicable to

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most watershed management needs. The basic camera package currently utilized for most flights is a four camera 70 mm format, multispectral array and a Wild RC-10, 6-inch (152 mm) focal length camera. The four matched 70 mm cameras with 45 mm focal lengths are coupled to provide simultaneous images in discrete portions of the photographic spectrum similar to those images provided by LANDSAT. Each matched set of 70 mm images covers an area about 21 km square (approximate scale 1:445,000) with an average ground resolution of 12 m. The Wild RC-10 is a high quality, calibrated mapping camera using 9½-inch (240 mm) wide film. Each scene from the RC-10 covers an area about 30 km square (approximate scale 1:130,000) with an average ground resolution of 7 m. Color infrared imagery (0.51 - 0.90 μ m) is usually taken with the RC-10 camera. A variety of other longer focal length cameras, in various configurations, and electro-optical sensors are available for special purpose flights as required.

Because of the small and medium area coverage obtainable from aircraft, data availability is somewhat restricted for many potential study areas. Spacecraft provide the advantage of repetitive, regional monitoring of dynamic hydrologic systems over any area of interest, sometimes at reasonably high resolutions. LANDSAT 1 and 2 are identical vehicles with orbital characteristics that bring each satellite over any given point on the earth once every 18 days. Each satellite makes 14 orbits a day, viewing a 185 km wide data swath on the earth's surface each orbit. Southward equator crossing occurs at approximately the same time each day - about 0942 local solar time. This orbital configuration provides a day-to-day sidelap of the data swaths of 14% at the equator; because of the near-polar orbit, the sidelap increases to more than 80% at high latitudes and thus allows daily coverage for periods as long as 6 days in the polar regions. At the time of this writing both LANDSAT 1 and 2 are operating, and the orbital configurations are such that the two satellites effectively provide coverage over any point on the surface once every nine days.

The LANDSAT payload consists of the following elements:

1. Multispectral scanner subsystem (MSS). The MSS scans horizontally along the orbital track in 4 spectral bands: green (0.5-0.6 μ m), red (0.6-0.7 μ m), and 2 near-infrared bands (0.7-0.8 μ m and 0.8-1.1 μ m). During ground processing, 70-mm image frames of areas 185 km square are produced. The ability of the MSS to resolve objects on the earth's surface varies depending on the geometric characteristics of a given object and its contrast with surrounding features; generally the MSS achieves a spatial resolution capability near 80 m.
2. Return beam vidicon (RBV) television cameras. The RBV cameras view a successive 185- by 185-km areas in 3 different spectral bands: green (0.475-0.575 μ m), red (0.580-0.680 μ m), and near-infrared (0.698-0.830 μ m). This system is currently on standby status on both satellites.
3. Data collection system (DCS). The DCS is not a remote sensing experiment but is rather a communications system. It collects information from some 150 remote, unattended, instrumented ground platforms and then relays the information to NASA ground stations for delivery to the users.

Skylab experiments in 1973-74 provided additional high quality space data for water resources studies. The Skylab Earth Resources Experiment Package (EREP), at a nominal altitude of 435 km, used visible light and near-infrared photography and infrared spectrography, an electromechanical scanner, and sensors for microwave surveys. The first manned Skylab mission (SL-2) was from 25 May 1973 to 22 June 1973 and included only 11 earth resources data passes. The second mission (SL-3) from 28 July 1973 to 25 September 1973 increased the earth resources passes to 44 and the third mission (SL-4) from 16 November

1973 to 8 February 1974 had 55 earth resources passes. Over 35,000 frames of imagery were obtained in addition to vast amounts of magnetic tape data.

The EREP sensors of prime interest are the six-band multispectral photographic camera (S-190A) and the earth terrain camera (S-190B). The S-190A spectral band images included the visible and near infrared portions of the spectrum with resolutions ranging from 30 to 79m and covering areas 163 km square. The S-190B produced high resolution color, black and white, or color infrared images covering areas 190 km square. Depending on the film used, resolutions ranged from 17 to 30m. Because of the relatively short data collection period, Skylab was not able to provide the regular repetitive coverage available from LANDSAT but was able to produce the highest resolution earth resources photography from space available to date.

On 15 October 1972 the National Oceanic and Atmospheric Administration's NOAA-2 satellite was launched inaugurating a series of medium resolution environmental satellites. Since then NOAA 3 and 4 have also been placed in orbit. NOAA-2 is in a near-circular, sun-synchronous orbit at a nominal altitude of 1500km. It crosses the equator southbound at 0851 local solar time and provides two views of North America daily, one at about 1000 and one at about 2200 (local time). The orbital characteristics of NOAA 3 and 4 are very similar to NOAA-2.

The payload of the NOAA environmental satellites includes a number of sensors, but the one of major interest is the Very High Resolution Radiometer (VHRR). The VHRR is a dual-channel scanning radiometer sensitive to energy in the visible spectrum (0.6–0.7 μm) and in the infrared (10.5–12.5 μm). The instantaneous field of view is designed to be 0.6 mrad for both channels. Ground resolution is approximately 0.9 km at the subpoint. Although the VHRR is designed primarily for direct readout service, a tape recorder provides a maximum of 8½ minutes of recorded data per orbit.

Table 1 summarizes the characteristics of remote sensing systems and data which are currently available to the water resources community for use in watershed management. The following section describes how some of these data sources have been applied to water resources problems.

Table 1—Characteristics of Remote Sensor Systems Applicable to and Available for Water Resources Management

Vehicle/Sensor	Spectral Bands (μm)	Area of Coverage (kilometers ²)	Nominal Resolution (meters)	Frequency of Coverage
U-2/Vinten multispectral cameras	0.475–0.575 0.580–0.680 0.690–0.760 0.510–0.900	425	12	variable
U-2/Wild camera	0.510–0.900	875	7	variable
Skylab/Earth terrain camera	0.4–0.7 0.5–0.7 0.5–0.88	11880	17–30	variable
Skylab/Multispectral photographic camera	0.4–0.7 0.5–0.6 0.5–0.88 0.6–0.7 0.7–0.8 0.8–0.9	26570	30–79	variable
LANDSAT/MSS	0.5–0.6 0.6–0.7 0.7–0.8 0.8–1.1	34225	80	once per 18 days (two satellite system provides coverage every 9 days over U.S.)
NOAA/VHRR	0.6–0.7 10.5–12.5	sub-continent	900	twice per day

RECENT REMOTE SENSING ADVANCES IN WATERSHED MANAGEMENT

Snow Mapping.—The most definite snowpack feature that can be extracted from spacecraft or aircraft is the area of the watershed covered by snow. The extraction of snowcovered area from satellites using visible and near infrared imagery has been tested successfully against low and high altitude aircraft measurements and thoroughly documented in handbook form (3). The extraction of other more meaningful snowpack parameters such as water equivalent and depth is still in the research stage, although water equivalent values obtained by measuring the snow's attenuation of natural gamma radiation from extremely low altitude aircraft have been very promising (4,16). Such techniques are not nearly operational, however, and it is fortunate that a good correlation has been observed between satellite-observed snowcovered area and snowmelt-derived streamflow (22). Two approaches were used to investigate relations between snow extent and runoff. Initially a large watershed without significant upstream diversions (the Indus River above Attock, Pakistan) was monitored from 1967-1972 using low resolution, meteorological satellite data and International Hydrological Decade streamgauge records. The average area covered by snow near the beginning of April was related in a simple regression analysis to runoff occurring from 1 April to 30 June. The regression relation shown in Figure 1 was significant at the 99% level.

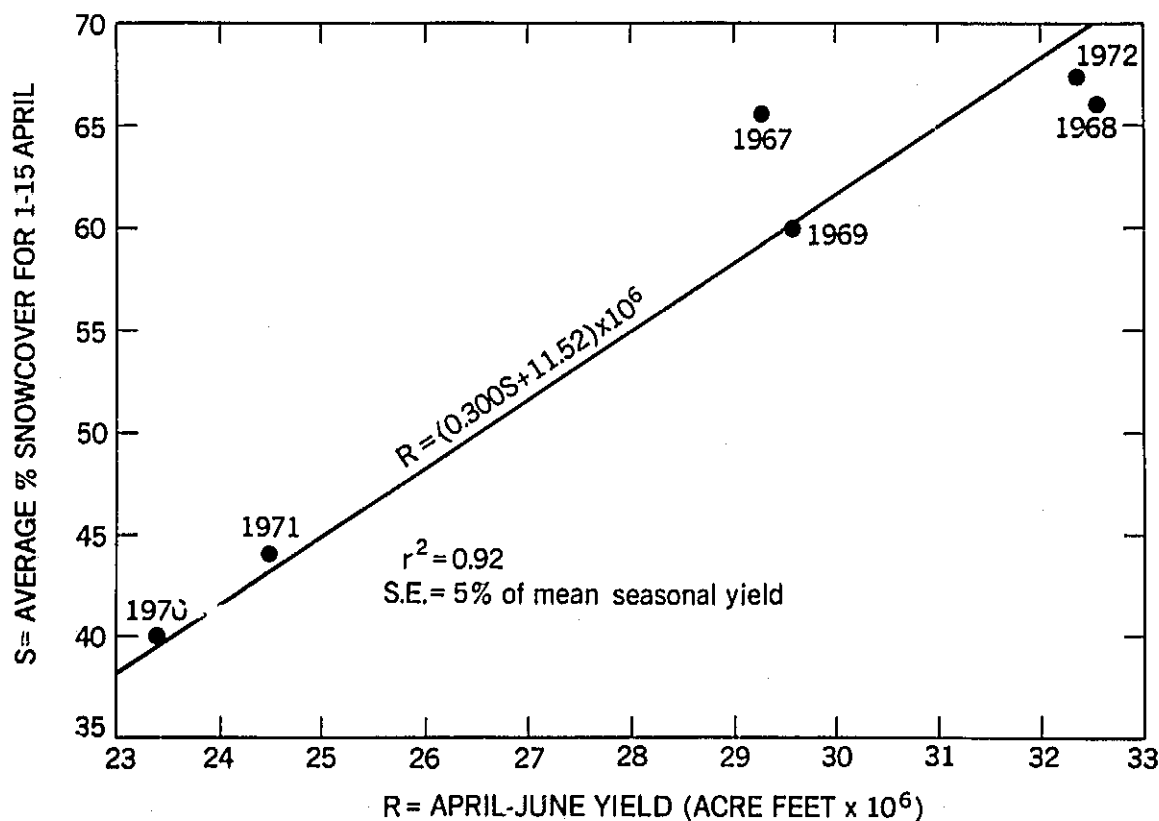
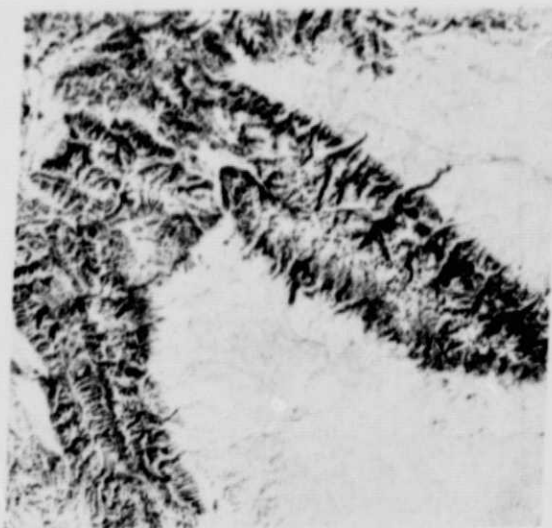


Figure 1. Satellite-Derived Snowcover Estimates Versus Measured Runoff for the Indus River, 1967-1972.

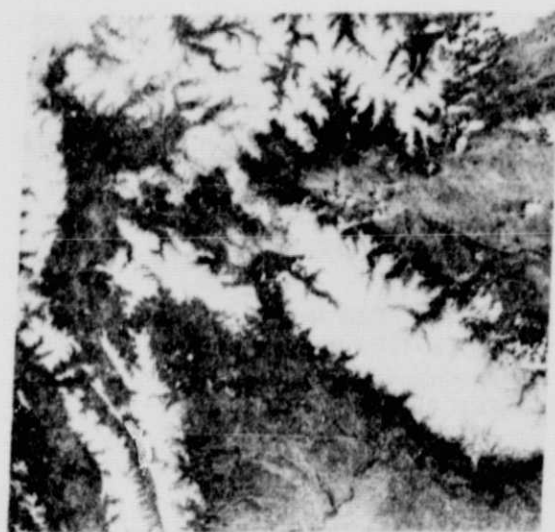
Subsequent examination of the shorter term, but higher resolution, LANDSAT data in the Wind River Mountains of Wyoming indicated that similar relationships existed on watersheds as small as 200km². Figure 2 shows the annual variation of snowcover in the Wind River Mountains during the 1972-1973 snow season. The snowcovered area was measured in detail on seven small watersheds for two years. Three watersheds were classified as high



6 AUGUST 1972



10 DECEMBER 1972



21 MAY 1973



8 JUNE 1973

Figure 2. LANDSAT Observed Snowcover Changes in Northwestern Wyoming, 1972-1973.

elevation ($>3,050\text{m}$ mean elevation) and four watersheds were classified low elevation ($<3,050\text{m}$ mean elevation). The specific watersheds in these two classes were assumed to be similar for purposes of producing a composite data base with more than two points. The snowcovered area on 15 May was measured and related to the 15 May-31 July streamflow for each group of watersheds for the two years. Resulting regression relations were also significant at the 99% level. Figure 3 illustrates these relations for the low elevation watersheds.

Although rough estimates of runoff could be made using the equations shown in Figures 1 and 3, the importance of such relations rests in the fact that the differences in the areal snow extent as observed from space are quantitatively related to snowmelt runoff and, as a result, indirectly related to the volume of water on a watershed. Satellite snowcovered area data, in combination with conventionally gathered data, should be most effective as an additional index parameter for seasonal streamflow forecasting and should be useful for reducing errors associated with current prediction techniques. These same snow extent data should be of value to the few watershed models requiring snowcovered area inputs.

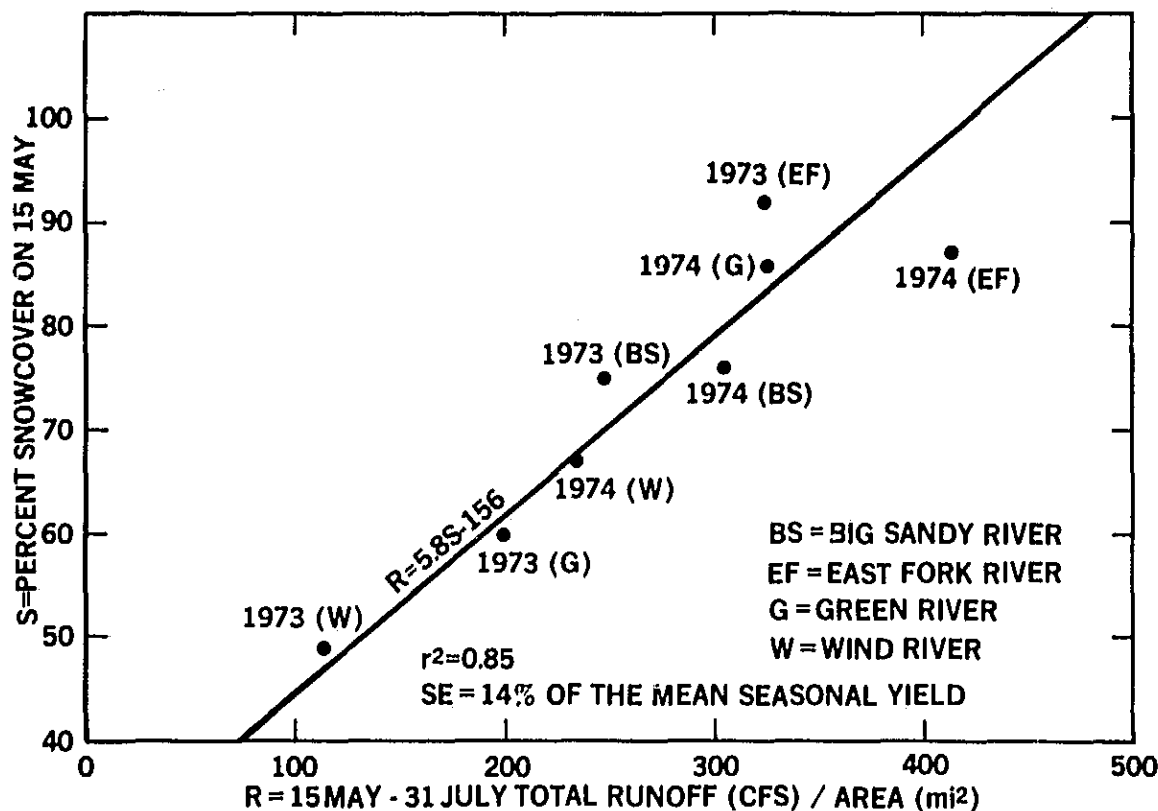


Figure 3. LANDSAT Derived Snowcover Estimates Versus Measured Runoff (1973 and 1974) for Four Watersheds Less than 3,050 meters Mean Elevation in the Wind River Mountains, Wyoming.

Because of the promising aspects of satellite snowcover mapping, NASA is currently sponsoring a cooperative demonstration project dealing with the operational applications of satellite snowcover observations. Federal agencies such as the U.S. Geological Survey, U.S. Bureau of Reclamation, Bonneville Power Administration, U.S. Soil Conservation Service, U.S. Army Corps of Engineers, and the National Oceanic and Atmospheric Administration and state agencies such as the California Department of Water Resources, Colorado Division of Water Resources, and the Arizona Salt River Project are currently attempting to test the satellite data by incorporating them into their operational procedures. This project includes four major study areas and 17 watersheds in the West. The studies underway are employing hydrologic modeling, regression analysis, low altitude aircraft flights, calculation of melting snow areas, and the LANDSAT data collection system in addition to basic photo interpretation. Results and cost/benefit analyses from this project will be fully documented.

Surface Water Inventories.—High resolution, near infrared sensors such as those on LANDSAT can be used to definitely measure the extent of surface water because of the strong near infrared contrast between water and adjacent land. Numerous results from LANDSAT studies indicate that water bodies as small as 0.01 km^2 can be delineated with ease. This makes the monitoring of surface water using LANDSAT feasible, even on small, inaccessible watersheds. The U.S. Army Corps of Engineers has been employing LANDSAT data for locating and counting bodies of water larger than 0.02 km^2 , calculating their area, identifying their shape, and locating dam sites on major rivers in response to Federal legal requirements (17). For larger water bodies LANDSAT has also proven useful. Goddard Space Flight Center has recently supplied the U.S. National Committee for the International Hydrological Decade with a computer printout noting the location, surface water area, and north-south and east-west maximum dimensions of the 128 surface water bodies in the U.S. that cover

more than 100 km² as measured from LANDSAT. These data will be used as part of a global surface water inventory. One drawback of using LANDSAT is that for lakes less than 10 km² the data reduction and processing becomes formidable for large area surface water inventories.

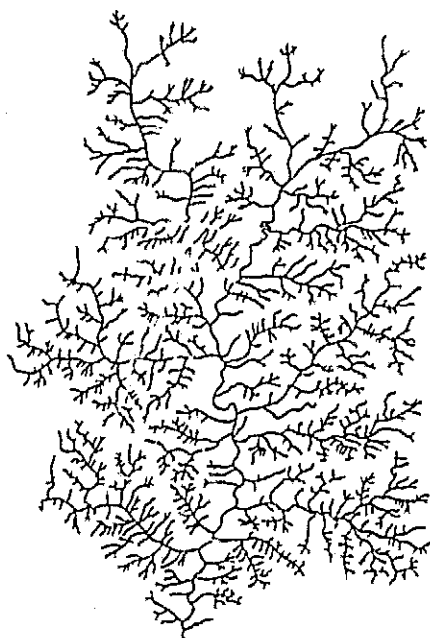
Flood Assessment and Floodplain Mapping.—LANDSAT data are the most pertinent kinds of satellite information for flood observations because of the relatively high resolution, cartographic fidelity, and the near infrared sensors. Mapping of floods using LANDSAT data has been reported by Hallberg, Hoyer, and Rango (13), Deutsch and Ruggles (9), Rango and Salomonson (19), and Williamson (29). Areas inundated are detected in the near infrared LANDSAT bands as areas of reduced reflectivity due to standing water, excessive soil moisture, and vegetation moisture stress. Most important is the fact that LANDSAT observations as late as two weeks after the flood crest will still show the characteristic reduced near infrared reflectivity of the previously inundated areas, which essentially reduces the need for obtaining satellite observations at the time of peak flooding. Other investigations (6,20) have shown that areas likely to be flooded, known as floodprone areas, tend to have multispectral signatures which are at times different than the signatures of surrounding non floodprone areas. The floodprone areas have unique natural vegetation and soil characteristics as well as different cultural features acquired over a long period of time in response to increased flooding frequency that enable them to be distinguished from the non floodprone areas. The same investigations cited above have also shown that the LANDSAT floodprone area signatures have, as yet, an unexplained correlation with the 100 year flood engineering and legal boundaries. The reasons for these fortuitous correlations are currently being investigated using LANDSAT digital data.

Flood and floodprone area observations from LANDSAT are indeed promising, but only on a regional basis. Most satellite photographic flood mapping has been done at 1:250,000 scale. Digital LANDSAT flood and floodprone area maps have been produced at 1:24,000 and 1:62,500 scales, but they do not meet national map accuracy standards. For many legal requirements it is necessary to generate products at even larger scales. As a result flood assessment on small watersheds must generally be done using high resolution, color infrared photography such as available from the U-2. Such imagery provides the needed resolution for mapping inundated areas. The detection of floodprone areas at required legal scales has also been performed using aircraft data (14). It appears that for most watershed management flooding applications, high resolution aerial photography is the basic and necessary tool. LANDSAT data can be used to provide an excellent regional flooding overview (and on large watersheds) as well as a temporal floodplain monitoring capability. Until higher resolution satellite data are available, however, aircraft will provide the most meaningful data.

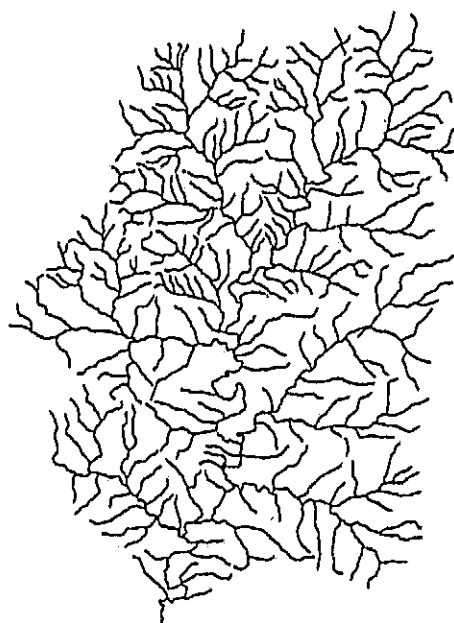
Hydrologic Land Use Analysis.—Knowledge of watershed land use is important because a record of surface cover characteristics can be used to refine estimates of the quantity, quality, and timing of water yield in response to a particular precipitation event or watershed treatment. Various watershed models require up-to-date land use inputs for calibration purposes and, hence, better streamflow simulations. These land use requirements can be met by various levels of remote sensing data. It is generally agreed that valuable land use maps can be produced from LANDSAT data at 1:62,500 and 1:24,000 scales (2,18). Extraction of such data from LANDSAT information is being carried out at Goddard Space Flight Center using digital multispectral classifications on the Patuxent River watershed. The data from this study have been used to calibrate a parametric hydrologic model on a particular subwatershed 80 km² in area. Results from this study indicate a number of weaknesses in data extraction capabilities. First, LANDSAT data from one date alone cannot be used to classify land use of the entire watershed. Temporal data must be used to produce a total area land use classification. Secondly, using satellite data Level I (forest land as an example) and only some Level II (deciduous forest as an example) land use classes can be obtained

because of resolution limitations. If more detailed land use information is desired, the high altitude U-2 data must be used. Results indicate that all information desired by a planning agency could be supplied by this data source. Data extraction is much more difficult and expensive from aircraft, however, because it is not as easy to acquire and not as amenable to automatic extraction as satellite data are. U-2 color infrared photography over the Patuxent River watershed, however, has been digitized and used in automatic classification programs in the same way as LANDSAT data. Results are similar to LANDSAT, but more detailed.

Physiographic Characterization.—Physiographic observations such as basin area and shape, stream network organization, drainage density and pattern, and specific channel characteristics can enable an investigator to estimate the mean annual discharge and mean annual flood flows from a watershed, as well as the rapidity of watershed response to a particular rainfall event. In general, the kind of dynamic hydrologic information available from the repetitive coverage of LANDSAT cannot be obtained from topographic maps. Further, in some areas single LANDSAT images offer more geomorphic information than is available on comparable scale maps (28). In a study covering a variety of U.S. physiographic regions, Rango, Foster, and Salomonson (21) found that watershed area, watershed shape, and channel sinuosity measurements from LANDSAT are generally comparable to similar physiographic measurements derived from topographic maps regardless of study area. Drainage networks are well delineated in areas of dissected topography with detail on 1:100,000 scale LANDSAT enlargements commensurate with information on 1:62,500 scale topographic maps (see Figure 4). Low order streams are difficult to detect in heavily vegetated areas with little local relief or in areas where stream channel development is limited. In such areas LANDSAT derived drainage densities tend to be less than those obtained from equivalent scale topographic maps. Temporal LANDSAT analysis slightly improves physiographic detail in these areas, however, marked improvements in feature discrimination are obtained only by using high altitude U-2 photography. The combination of these two remote sensing platforms allows for the extraction of all physiographic parameters necessary for a watershed analysis, except for detailed channel dimensions.



LANDSAT 1:100,000 SCALE ENLARGEMENT OVERLAY, JANUARY 2, 1973



USGS 1:62,500 SCALE TOPOGRAPHIC MAP OVERLAY

Figure 4. The Drainage Network of the Kickapoo River (above La Farge) Extracted from LANDSAT Imagery and U.S. Geological Survey Maps

Watershed Models—Much of the information capable of being extracted with the remote sensing approaches mentioned previously can be used in the calibration or operation of numerical watershed models, especially in data sparse regions. The suitable data include land use classifications, stream channel and other physiographic parameters, and snowcovered area. The question that must be answered is whether the necessary data can be extracted with remote sensing at the appropriate scale or accuracy. One parameter required of most models is watershed impervious area. This parameter consists of a combination of specific land uses including urban development, streets, parking lots, roof tops, and construction sites. The extraction of an integrated percent of impervious area parameter would be exceptionally useful and has been investigated on the Anacostia River watershed in Maryland by Ragan (unpublished results, 1975). LANDSAT automatic classifications of impervious area were compared to results from an earlier study which employed manual measurements taken off low altitude, large scale aerial photographs. Approximately 94 man days were required to complete the required land use analysis using the aerial photographs. Less than three man days were required to accomplish similar tasks using the LANDSAT data. Analysis of the LANDSAT data provided an estimate of the basin imperviousness of 19% whereas the aerial photographic study had resulted in a 24% figure. Agreement between the conventional photographic method and the LANDSAT approach was excellent for subwatershed areas as small as 1.48 km². Ragan (unpublished results, 1975) felt that the correspondence between the two methods was more than adequate for any of the hydrologic model impervious area input requirements.

In addition to this study, a sensitivity analysis has been performed which has identified the input parameters in the Kentucky Watershed Model that are amenable to current remote sensing systems (1). The input parameters that can be obtained with remote sensing at an acceptable accuracy include watershed area, fraction of impervious area, water surface fraction of the basin, vegetation interception maximum rate, mean overland flow surface length, overland flow roughness coefficient, and fraction of the watershed in forest. Other parameters have been identified as potentially extractable as improvements in image interpretation and analysis techniques become available and new remote sensing methods are developed. Tests are currently being conducted using existing map data and up-to-date information from remote sensing to determine if remote sensing-based model calibrations provide any better streamflow simulations than calibrations based on conventional data. Numerous models, watersheds, and kinds of remote sensing data are being evaluated at Goddard Space Flight Center to come up with some definitive conclusions regarding the applicability of remote sensing for watershed modeling.

Data Collection System.—The collection of certain hydrologic information, such as river stage, snow water equivalent, water quality, and groundwater level is not presently amenable to operational remote sensing. Nevertheless, accurate and rapid observations of these parameters are needed, and satellites provide a dependable means of collecting and relaying this information. The LANDSAT data collection system (DCS) has demonstrated the use of this capability in several instances (7). Some 150 data collection platforms (DCP) are in operation across the United States. At these DCP's, conventional hydrologic measurements are made and relayed via the satellite to the user in near-real time. In Arizona, for example, during the unusually large snowmelt events that occurred during the spring of 1973, data from the LANDSAT DCP's provided essential snowmelt-runoff information in time periods of less than one hour. This hydrologic information considerably improved the management of water runoff in the Salt and Verde River watersheds and lessened the inconvenience due to flooding in the Phoenix area. In general the reliability of the DCS has been demonstrated to be comparable or better than ground-based microwave telemetry relay systems in all cases tested. The Geostationary Operational Environmental Satellite (GOES) provides an additional data collection system that permits continuous 24-hour interrogation of sensors over large areas. Recent research has seen more attempts to integrate the DCS data and the satellite images in order to more completely characterize the basin hydrologic cycle.

DEVELOPING FUTURE REMOTE SENSING CAPABILITIES

Soil Moisture Determinations.—Although soil moisture is one of the most important parameters needed for solving water balance equations for watersheds, remote sensing techniques for assessing soil moisture are currently being developed and have yet to be fully tested. LANDSAT multispectral observations seem to enable relative estimates of soil moisture based on the differential response of wet and dry soils, which is most pronounced toward the near infrared LANDSAT bands. Additionally, multispectral soil mapping with LANDSAT data has been effective in certain areas, generally where vegetation is sparse. In these sparsely vegetated areas, variations in reflectivity appear to be related to moisture in the near-surface soil. The fact that only qualitative inferences about surface soil moisture can be made in bare soil areas does not allow LANDSAT to be used effectively for moisture balance determinations.

The use of thermal infrared data to detect soil moisture variations has been considered based on experiments in Arizona (15). These experiments indicated that the greater the soil moisture percentage by weight, the less the diurnal surface temperature variation. If these initial variations hold true in future studies, thermal infrared data from the VHRR on the NOAA satellites (and other sensors) should be useful in detecting quantitative soil moisture variations that would be useful in irrigation planning. The effect of vegetation is largely an unknown factor, however, and must be evaluated by further research efforts.

Passive and active microwave frequencies are very interesting for soil moisture monitoring because microwave radiation penetration capabilities reveal some information about the make-up of the subsurface. Since the dielectric constant of water at microwave frequencies is quite large (as much as 80), whereas that of dry soil is typically less than 5, the water content of a soil can greatly affect its dielectric properties (24). Recent experiments with airborne microwave radiometers flying over unvegetated terrain indicate that microwave brightness temperature is a function of the wavelength of the radiometer and the distribution of moisture in the soil. It appears that the longer the microwave wavelength, the greater the soil penetrability and the greater the information about soil moisture with depth. Even the shorter microwave wavelengths produce much valuable near surface soil moisture data. In general, the greater the soil moisture percentage by weight, the less the microwave brightness temperature. Soil properties have a much greater influence on the microwave return at short wavelengths (1.5 cm) than at long wavelengths (21 cm). Studies are continuing on the effects of vegetation and surface roughness on the microwave emission from the soil (24).

In December 1972, NASA launched the Nimbus 5 satellite carrying on board the electrically scanning microwave radiometer (ESMR). This coarse-resolution passive microwave instrument ($\lambda = 1.55$ cm) provides a capability for monitoring surface and near-surface moisture features over extremely large areas. In an initial study using early ESMR data over the Mississippi Valley, the microwave brightness temperature fluctuations were compared with a number of known hydrologic parameters. The correlations were best with precipitation, indicating that ESMR is indeed monitoring soil moisture changes in a layer just beneath the surface (25). Such observations may provide an index of the susceptibility of a particular area to flooding or its readiness for the application of irrigation water. Watershed studies will not benefit from such information, however, until markedly improved resolution sensors are available. Active microwave experiments show additional promise, but research in this area is only beginning and definite results are not yet available.

Future Space Systems.—A number of satellites are currently in operation and a number of new vehicles will be launched in the next ten years. Varying frequency of coverage and spatial resolution capabilities permit different types of water resources phenomena to be observed with the various systems. Figure 5, adapted from Salomonson (23), shows a representation of various phenomena to be observed, time periods of observation, distance scales,

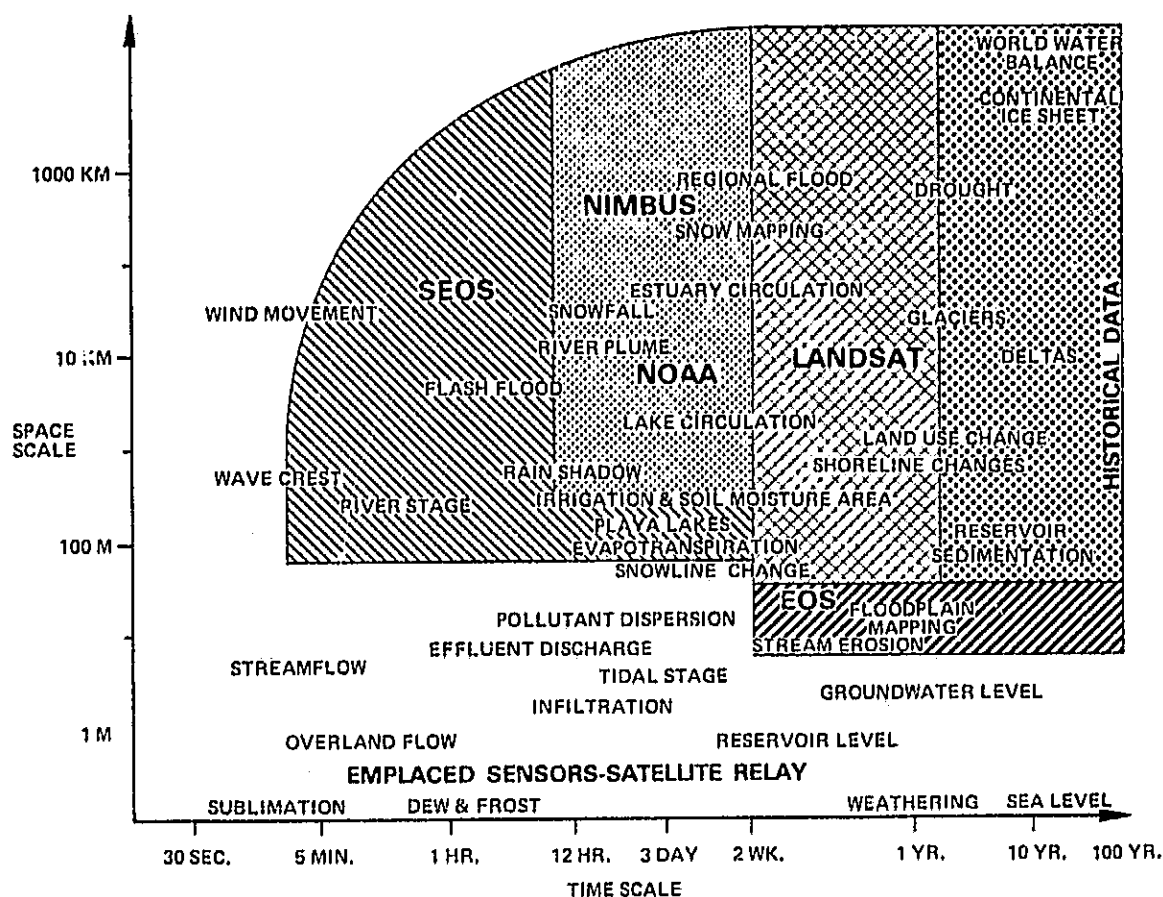


Figure 5. A Time Versus Space Scale Diagram Indicating the Observing Capabilities of Existing and Planned Spacecraft Systems

and capabilities of existing or planned unmanned spacecraft systems. As an example, LANDSAT generally observes various water resources phenomena no more than once every 18 days and identifies objects with at least one dimension 80 meters or greater. The other currently operating satellites, the Nimbus and NOAA series, are making observations once every 12 hours with resolutions as good as 0.9 km. Note in Figure 5 that many of the applications discussed in this paper are indicated in the areas covered by LANDSAT, Nimbus, and NOAA. The Skylab EREP sensors, when operating, had capabilities for irregular time interval observations with resolutions down to 17 m (Earth Terrain Camera). A possible follow-up to the LANDSAT satellites will commence with the launching of the Earth Observatory Satellite (EOS) series presently being considered for the late 1970's. EOS would have much the same sampling frequency and types of sensors as LANDSAT, but the spatial resolution capability would increase to 10 meters over small study areas. Beyond the EOS program, starting sometime after 1980, is a series of Synchronous Earth Observation Satellites (SEOS) which will be able to make observations every few minutes, if desired, at about 100 meter resolutions. Observations from synchronous altitude will be possible by placing a very large telescope ahead of presently available remote sensors. These rapid observations will make possible a better remote sensing characterization of dynamic hydrologic events.

The applications and satellites listed in Figure 5 refer only to sensors currently available and not to the development of new or refined instruments. Certainly other portions of the electromagnetic spectrum will be exploited in following years. The Skylab EREP program with its many varied sensors was an excellent start in the direction of evaluating the advantages of observations in various regions of the spectrum not commonly used. The

ERAP program is also contributing a great amount of information leading to the development and flying of new instruments. Microwave applications will probably be in the forefront of research efforts extending into the 1980's.

Future remote sensing systems will most likely consist of the above satellites with various sensors coupled with satellite data collection systems to rapidly make available conventional hydrologic data. Complimenting this will be data acquisition missions conducted with high, medium, and low altitude aircraft and limited ground based surveys. In order to make sense out of this large amount of water resources data, sophisticated, rapid, and flexible automatic data processing systems have to be developed to disperse the pertinent hydrologic information to the operational agencies.

Familiarization With Remote Sensing-Watershed Management Capabilities.—In cases where a watershed manager may feel that a particular remote sensing technique may be able to provide him with a desired answer, a lack of knowledge of how to use the data or even where to obtain it prohibits the use of remote sensing. Some ways are suggested here to enable the potential user to become familiar with remote sensing techniques. First, several handbooks or compilations of scientific papers specifically pertinent to water resources exist that would provide a good background for certain water resources applications. The American Water Resources Association has published the proceedings of a symposium on Remote Sensing and Water Resources Management that provides a broad spectrum of the applications of both airborne and satellite acquired data to water quantity and quality monitoring (27). As a result of the fact that snowcover extent mapping has produced a number of positive results, an excellent manual entitled Handbook of Techniques for Satellite Snow Mapping (3) has been compiled. This snow handbook emphasizes the use of NOAA and LANDSAT but also provides a complete description of other possible satellite snow data sources. The U.S. Army Corps of Engineers has produced a number of documents outlining the applications of remote sensing to water resources that are quite useful. The Cold Regions Research and Engineering Laboratory in Hanover, New Hampshire has documented the methods to use for locating reservoirs with surface water extent greater than 0.02 km² (17). The Hydrologic Engineering Center in Davis, California has published a report on remote sensing applications in hydrologic engineering (5). The third Corps of Engineers document is a manual on remote sensing practice and potential put out by the Waterways Experiment Station in Vicksburg, Mississippi (30).

In order to use LANDSAT (ERTS) data most efficiently it may be helpful to obtain The ERTS Data User's Handbook (8). These may be obtained for a nominal fee from the General Electric-ERTS Liaison Office in Beltsville, Maryland.

Once a basic knowledge of remote sensing capabilities is acquired, probably the best way to specifically become acquainted with advantages of remote sensing for a particular watershed problem is to obtain some data over the area of interest. These data can then be perused and compared to previous knowledge and conventionally available data to develop a familiarity with the potential uses. The primary place to order remote sensing data is The Earth Resources Observations Systems (EROS) Data Center of The U.S. Geological Survey in Sioux Falls, South Dakota. LANDSAT, Skylab EREP, and high altitude ERAP data can be obtained from EROS at cost by the user. Area to be covered, permissible cloud cover, and type of imagery is the only information necessary for ordering. In the case of LANDSAT data, complete catalogs of acquired imagery are also available from EROS at a nominal charge. A catalog of Skylab earth resources data has also been published by NASA that facilitates ordering of EREP data (26). LANDSAT data may also be ordered from the National Oceanic and Atmospheric Administration's (NOAA) Earth Resources Data Center at Suitland, Maryland and from the U.S. Department of Agriculture, Agricultural Stabilization and Conservation Service, Western Aerial Photo Laboratory in Salt Lake City, Utah.

NOAA-VHRR data can be obtained from The National Environmental Satellite Service, Visible Products Support Branch in Suitland, Maryland. Information on Nimbus data availability can be obtained from the NASA National Space Science Data Center, Greenbelt, Maryland.

The EROS Data Center, in addition to distributing remote sensing imagery, provides the user with data interpretation assistance through consultation with specialists. Specialized remote sensing equipment is available for users at EROS, as well as several formal workshops and remote sensing training courses. Other remote sensing courses are offered by various Universities with remote sensing specialists on their faculty. For situations where the remote sensing solution to a particular user problem has not been previously demonstrated or documented, and the solution is not routinely available from facilities such as EROS, NASA's Goddard Space Flight Center in Greenbelt, Maryland is currently establishing an Information Transfer Laboratory (INTRALAB). INTRALAB will serve to transfer the most recently developed remote sensing technology directly to specific user application problems. It is hoped that the results of the studies performed in INTRALAB will benefit not only the user but also provide NASA with significant input for planning future sensor and data processing systems.

CONCLUSIONS

Today's aircraft and satellite remote sensing systems (operational and experimental) are capable of contributing greatly to watershed management, primarily in the areas of snow mapping, surface water inventories, flood management, hydrologic land use monitoring, and watershed modeling. As the technological advances in remote sensing of hydrological data continue to accelerate, so must the watershed management community expand its awareness of and its training in remote sensing techniques if these new tools are to be put to optimum use.

APPENDIX I--REFERENCES

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